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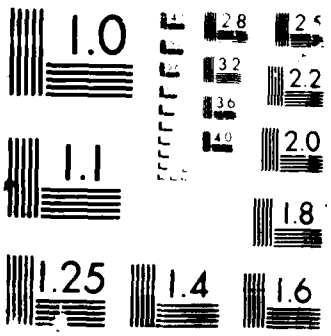
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The aim of this work during the last year has been to carry out research on new types of optical microscopes which gives better resolution in both the transverse and range directions than standard high-quality optical microscopes. The reason for carrying out such studies is that there is a need for measurements of semiconductor profiles with submicron resolution. The scanning electro microscope has excellent transverse resolution, but poor range resolution; it must be used in a vaccum, and it can damage sensitive semiconductor materials. We have been working with new scanning optical microscope concepts which provide excellent range resolution, of the order of 10nm, less, and transverse resolutions of the order of 200nm, and with computer processing as good as 130nm.

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APPLICATION OF NONDESTRUCTIVE TESTING TECNIQUES TO MATERIALS TESTING

by

G. S. Kino

INTRODUCTION

The aim of this work during the last year has been to carry out research on new types of optical microscopes which give better resolution in both the transverse and range directions than standard high-quality optical microscopes. The basic reason for carrying out such studies is that there is a need for measurements of semiconductor profiles with submicron resolution. The scanning electron microscope has excellent transverse resolution, but poor range resolution; it must be used in a vacuum, and it can damage sensitive semiconductor materials.

We have been working with new scanning optical microscope concepts which provide excellent range resolution, of the order of 10 nm or less, and transverse resolutions of the order of 200 nm, and with computer processing as good as 130 nm.

We have been working on two main projects: the electronically-scanned optical microscope and the scanning optical confocal microscope with differential phase imaging.

PROGRESS DURING THE YEAR

The Electronically-Scanned Microscope

The electronically-scanned microscope uses a Bragg cell to scan an optical beam, as shown in Fig. 1. Our system is built into a modified Leitz

Orthoplan microscope, kindly loaned to us by the Leitz Company. The input signal f_b to the tellurium dioxide Bragg cell is changed from 50 MHz to 100 MHz to scan the beam over the full field of view. This corresponds to a field of view with approximately 500 resolvable spots. When an optical beam is passed through the Bragg cell, part of it, beam A, is undiffracted and part of it, beam B, is diffracted by an angle proportional to the frequency. The beams then pass through the objective lens of the microscope to form two focused spots on the sample. The undiffracted stationary spot is used as a reference. When both beams are reflected from the sample, they pass back through the objective lens and the Bragg cell and are diffracted by it. In this system, the undiffracted beam A is diffracted in its return path through the Bragg cell and leaves it in the same direction as the undiffracted returning beam A. The beams pass to a photodetector and the detected signal at frequency $2f_b$ is processed by a signal processing system controlled by a personal computer. The transfer lenses are used because the Bragg cell must be located at the back focal plane of the objective lens; this is inside the lens, which makes it necessary to locate the Bragg cell at an image of this back focal plane.

The signal at frequency $2f_b$ has an amplitude proportional to the amplitude of the scanned beam and a phase equal to the phase difference between the scanned beam and the reference beam. Since the phase ϕ of the beam is equal to $2k\Delta z$, where $k = 2\pi/\lambda$ is the wave number, λ is the wavelength, and Δz is the difference in height on the object of the reference spot and the scanned spot. Thus, if we can measure the phase ϕ to an accuracy of 0.1^o, we can determine the height to an accuracy of the order of 1 nm.

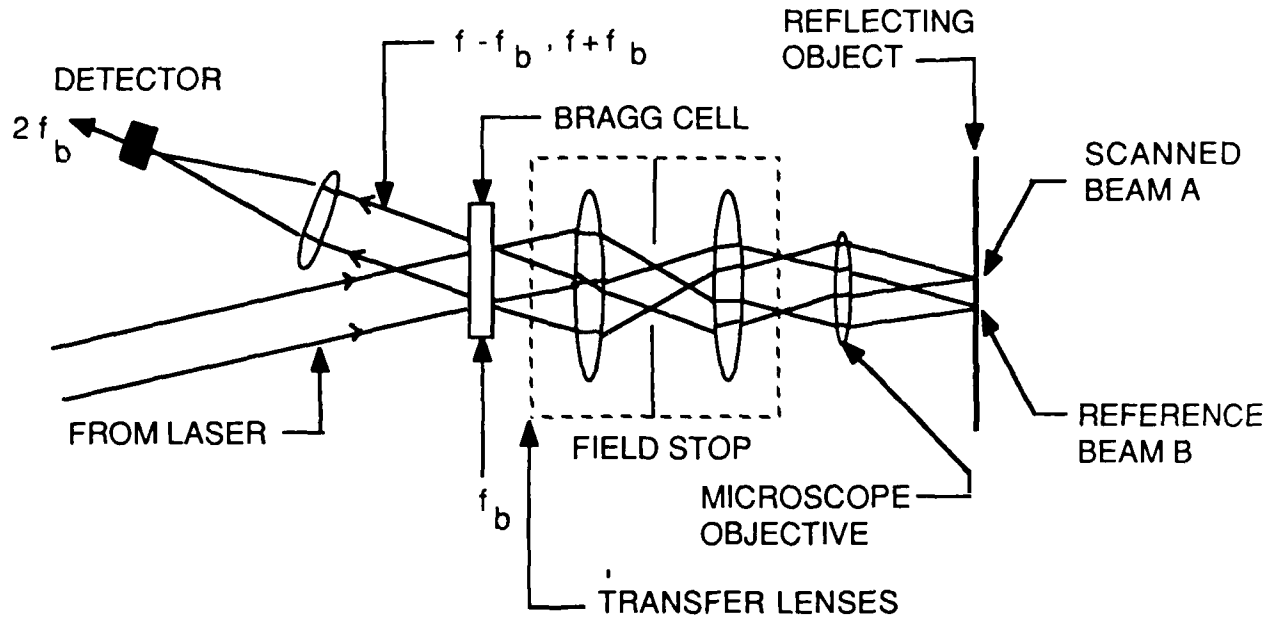

Fig. 1. Schematic of the electronically-scanned microscope.

We have constructed an electronic processing system which is capable of measuring amplitude and phase to this degree of accuracy in 20 μs. After trying several alternatives, we have devised a technique for measuring and calibrating the system with excellent accuracy.

We have used the system to measure profiles of metal films laid down on silicon, and metal films on glass and lithium niobate. In each case, since we can measure both phase and amplitude, we can separate out changes in height from changes in reflectivity. Typically, with a 510 nm argon laser beam, we can measure height with an error of a few nanometers, and the edge response from the 10-90% points of a step is 250 nm wide.

One major advantage of a system of this kind is that, since we have both amplitude and phase information available, it is possible to take a

spatial Fourier transform of the data. Using such techniques, we have carried out inverse filtering on a line scan of a sample, and have taken full advantage of the high spatial frequencies present in a confocal microscope of this kind. This has made it possible to reduce the width between the 10-90% height points on a step to 130 nm.

Results obtained with this system are described in more detail in accompanying papers.

The Mechanically Scanned Confocal Optical Microscope

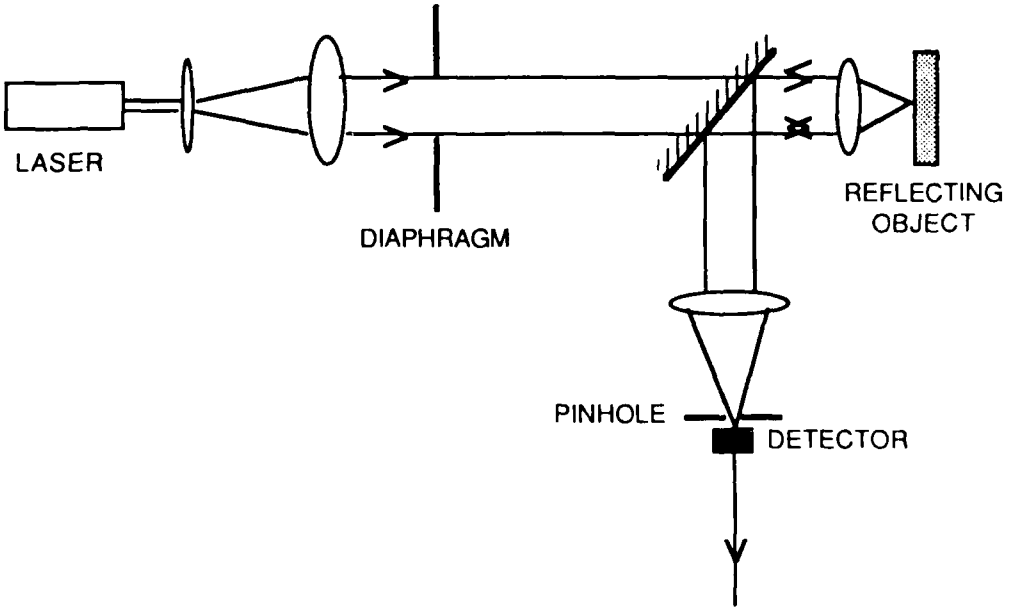

Fig. 2. A simplified schematic of a confocal microscope.

We have been developing a confocal mechanically-scanned microscope for some time. In this device, we illuminate the objective lens with a collimated beam; this forms a spot on the object. The reflected light from the object is passed via a beam splitter through a pinhole to a detector. When the object is at the focus of the lens, the reflected light is focused on

the pinhole and passes through it. However, when the object is moved out of the focal plane, the light is defocused and does not pass through the pinhole. Therefore, this type of microscope has very good range definition and is suitable for measuring profiles of semiconductors as well as being used for biological cross-sectioning. The transverse definition of the microscope is also better than a standard microscope because the lens is used twice; thus, the amplitude response is the square of the point spread function of the lens. The amplitude response of this type of microscope is therefore equivalent to the intensity of the response of the standard microscope. Images are formed in our microscope by mechanically scanning the object in a raster scan and using a scan converter to produce a video display. During the year, we have constructed a piezoelectric cantilever scanner and the necessary circuitry for obtaining high-quality images.

Phase Contrast Imaging

Our purpose has been not only to prove the principles of confocal microscopy, which are by now fairly well known. but also to arrive at new techniques for phase contrast and differential phase images, equivalent to the Zernike phase contrast and Nomarski differential phase systems, respectively.

The phase contrast systems which we are developing, yield a product signal between the reference and the sensing beams. Standard phase contrast systems only give a signal proportional to the sum of the two beams, so the contrast is far poorer than it is in our system. Furthermore, this type of system enables us to obtain two outputs at once, the standard intensity image of the confocal microscope and the phase contrast image. We believe that these systems will be particularly powerful for measuring

semiconductor profiles and they will be most important for the measurement of biological materials, which exhibit relatively small phase changes.

The Nomarski system uses a Bragg cell to split the beam into two parts. The input signal carrier of frequency ω to the Bragg cell is modulated by a frequency W. This produces upper and lower sidebands of frequencies $\omega + \Omega$ and $\omega - \Omega$, respectively, and hence two spots side by side. Using a frequency Ω of the order of 100 kHz, we can obtain two spots approximately a half spot width apart. The output signal has a frequency of 4Ω and a phase which is the phase difference between the two spots. Thus, by looking at the dc signal, we can obtain a standard confocal microscope output. By looking at the signal at 2Ω, we can also obtain a differential output. The differential output is particularly useful for observing the slope of a sample and determining where edges occur. A result obtained with this system is shown in the appendix. The edges appear as large peaks in the output.

The Zernike system is illustrated in Fig. 3. This uses an electro-optic cell made of a transparent piezo-optic material, PLZT. The electrodes for this cell are made of indium tin oxide and are transparent. One set of electrodes of radius R_1 cover approximately the center half of the cell. The outer set of electrodes of outer radius R_2 are grounded. When an ac voltage is applied to the center electrodes, the phase of the rays passing through this region is modulated periodically. When the periodically-modulated signal is detected, it can be shown that the output obtained at a

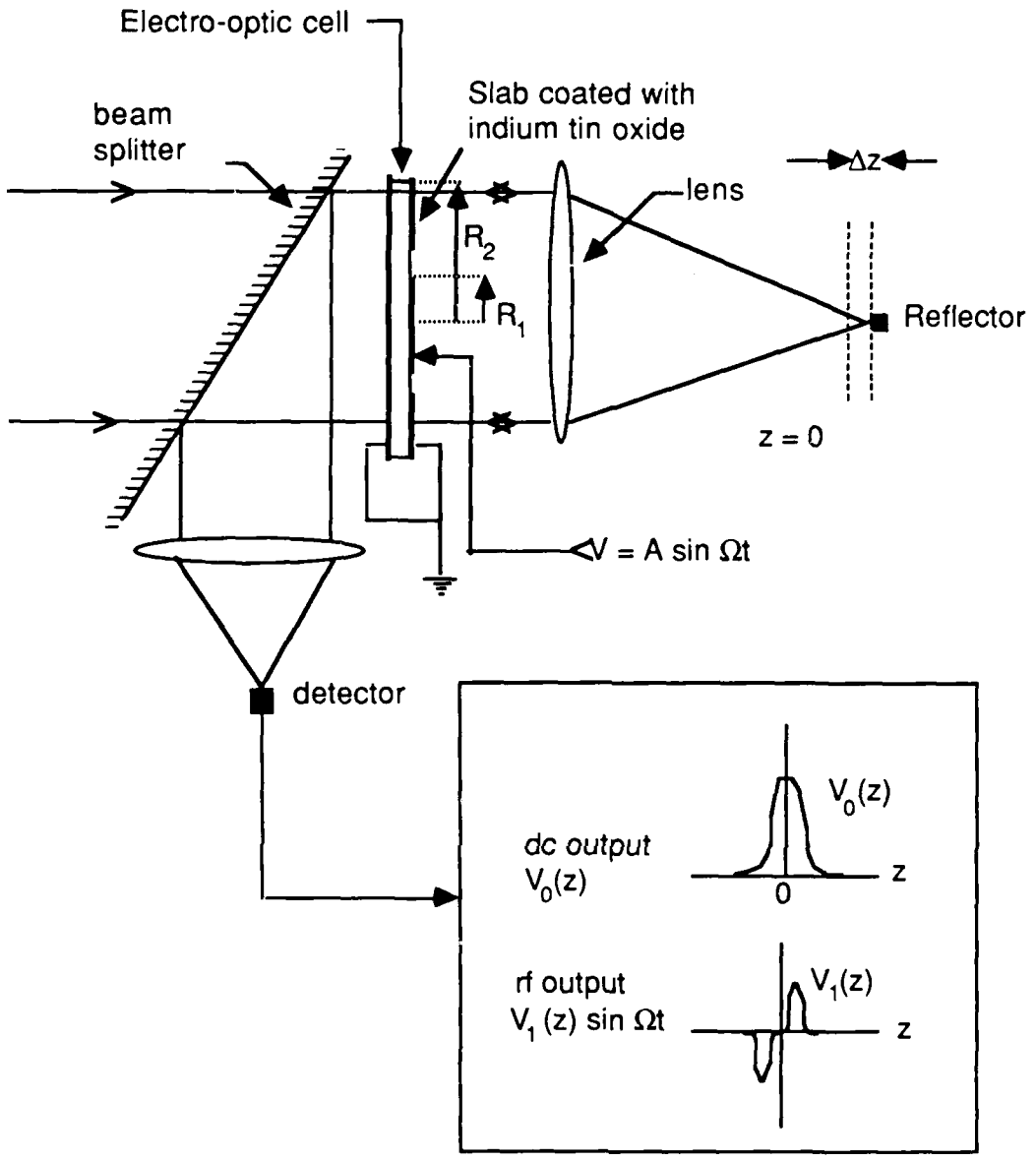

Fig. 3. Schematic of a modified Zernike phase contrast imaging system.

frequency Ω is zero on focus and varies linearly with distance Δz from the focus, at least over small distances. Therefore, the system is capable of detecting a linear change in phase. We have demonstrated the effect and we have shown theoretically that this is a far more powerful phase con-

trast system than a standard Zernike microscope because it does not have the same sidelobe amplitude.

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